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METEOROLOGICAL CONDITIONS CAUSING MAJOR ICE JAM FORMATION AND F--ETC(U)
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May 1982

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Meteorological conditions causing major ice jam formation and flooding on the Ottauquechee River, Vermont

Roy Bates and Mary-Lynn Brown

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This report discusses wintertime meteorological conditions that can induce rapid ice breakup, ice jam formation and subsequent flooding. These conditions, described for the Ottauquechee River in Vermont, should be representative of those for similar unregulated river systems in northern temperate regions. Summer flood conditions are compared to those during winter floods, when river ice is the main impediment to water flow. Comparisons are made for total precipitation, stage height and the synoptic meteorological situations

PREFACE

This report was prepared by Roy E. Bates, Meteorologist, and Mary-Lynn Brown, Sciences Aid, of the Geophysical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this study was provided by U.S. Army Corps of Engineers Civil Works Project, CWIS 31332, Fundamental Mechanics of Ice Jams.

The Hanover Meteorological Detachment of the Maynard, Massachusetts, Meteorological Team, U.S. Army Atmospheric Sciences Laboratory, was invaluable to this study, furnishing meteorological instrumentation and manpower for field sites as well as assistance in extracting the recorded meteorological data.

David Gaskin and Lawrence Gatto of CRREL technically reviewed the manuscript of this report.

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METEOROLOGICAL CONDITIONS CAUSING MAJOR ICE JAM FORMATION AND FLOODING ON THE OTTAUQUECHEE RIVER, VERMONT

by

Roy Bates and Mary-Lynn Brown

INTRODUCTION

The major objective of this study was to describe the meteorological conditions that induce ice jam formation and subsequent flooding on the Ottauquechee River in central Vermont. Other objectives were (1) to identify areas of the river prone to ice jamming, and 2) to compare ice-induced flooding to the severe summer flooding of 1973 so that the influence of ice on the flood events could be assessed.

CRREL monitored meteorological and ice conditions for three winters (1975-76, 1976-77, 1977-78) along the Ottauquechee River in the area of Woodstock, Vermont, and these results are presented in Bates and Brown (1981). Detailed measurements of *jamming and rafting* ice, as well as high water levels in both summer and winter, were observed at points along the Ottauquechee River. The detailed measurements not included in Bates and Brown (1981) are the subject of this report.

From 26 to 28 January 1976 and from 13 to 14 March 1977 severe ice jams occurred along the Ottauquechee River between Woodstock and Quechee, Vermont (see App. B). The ice jams resulted in significant local flooding. This report presents the meteorological and physical conditions prior to and during the flooding. Parameters examined include air temperature, precipitation, water equivalencies of the snow cover, river stage, condition of the ice cover, ice thickness and physical characteristics of the river.

ICE JAMS

All three winter periods (1975-76, 1976-77, 1977-78) monitored by CRREL personnel along the Ottauquechee River were characterized by the occurrence of ice jams in either December or January. For example two small ice jams unaccompanied by significant rainfall formed during 11-12 December 1976 (Fig. B4-B6) and 4-9 January 78. A third jam formed in late

January 1978 (24-26 January) as a result of a heavy rainstorm. During all three small ice jams, air temperatures never rose much above freezing.

Two severe ice jam/flooding conditions occurred in January 1976 and March 1977. In contrast to the three minor jams, the two severe jams were preceded and accompanied by abnormally warm wintertime air temperatures and heavy rainfall. A discussion of the two major ice jams follows.

1975-1976

During the period 26-28 January 1976 severe ice jamming and flooding was observed on the Ottauquechee River (Fig. B1-B3). Prior to the ice jam of January 1976, greater amounts of ice were observed in the Ottauquechee River than during the same period of the next two winters.

The January 1976 weather was characterized by abnormally high temperatures and heavy precipitation (for normals see U.S. Dept. of Commerce 1964, 1973). Within a few days, local maximum air temperatures rose to approximately 8°C (App. A), approximately 10°C above January's mean maximum temperature of -2°C. Concurrently, heavy rains fell on the existing snowcover.

In January, the precipitation for Woodstock, Vermont, was 164% of the normal amount and precipitation during the flood period accounted for over one half of this amount (Table 1, Fig. 1). Figure 1 shows that all three drainage basins - the Ottauquechee River, White River and Ompompanoosuc River - received greater than 60 mm (2.4 in.) of rainfall. The combination of above-freezing temperatures and heavy precipitation on a snow cover with an already high water equivalent (greater than 10 cm, Fig. 2) caused the river to rise (Fig. 3b, 3c), inducing extensive flooding and jamming.

Table 1. Precipitation comparison (mm) for selected local stations, January 1976.

Station	Normal precipitation	January 1976	% Normal	Amount of precipitation during flood	% January 1976 precipitation
Hanover	65	105	161.5	60	57.1
Woodstock	72	118	163.9	63	53.4
Rochester	69	148	214.5	88	59.5
Cavendish	75	106	141.3	58	54.7
Average	70	119	170.3	67	56.2

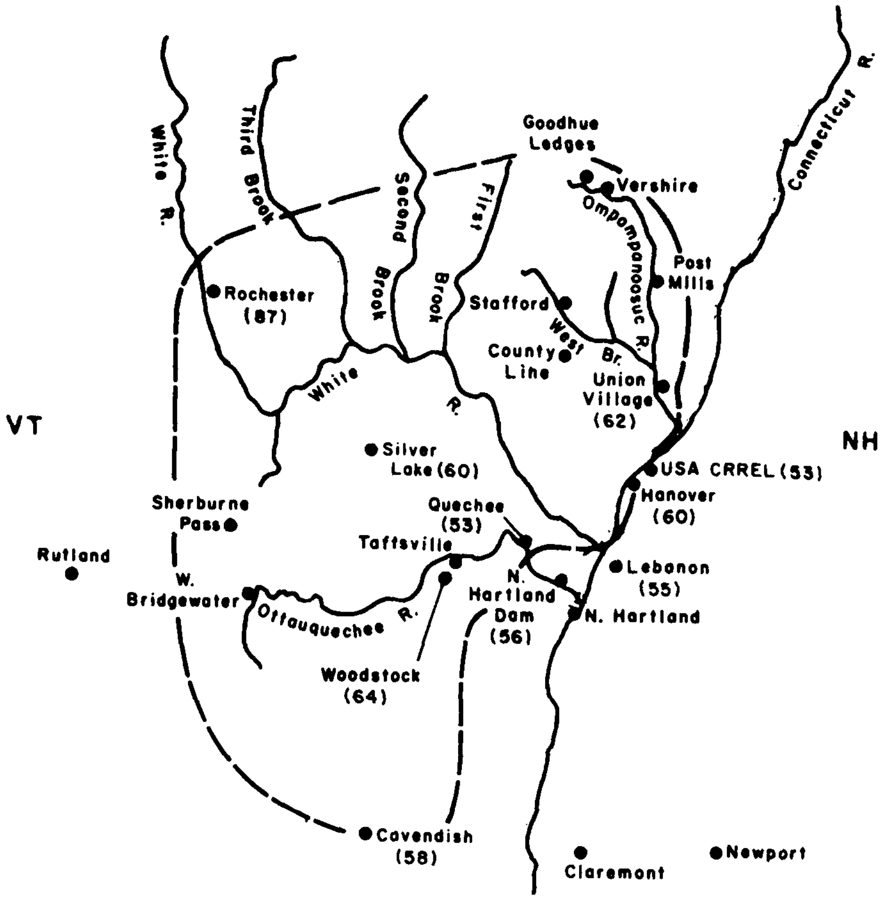


Figure 1. Amount of precipitation (mm) received during flooding of 26-28 January 1976. Dotted line = >60 mm of precipitation. Number = amount of precipitation. (Nearly all precipitation received was rainfall.)

The high water resulting from the thaw, rainfall and subsequent rafting and jamming of ice cleared the river channel of ice. Although ice reformed in February 1976, less than 10 to 15 cm of new ice growth was reported. The relative lack of new ice accumulation is attributed to the fact that the meteorological conditions necessary for ice formation (i.e. cold air temperatures of long duration) did not occur. The lack of ice growth, coupled with a slow warming trend in March, prevented any new ice jams on the Ottauquechee River.

1976-1977

An ice jam that formed on 11-12 December 1976 and froze in place on the Taftsville and Quechee mill ponds preceded the severe ice jam of 13-14 March 1977 (Fig. B4-B6). This early winter ice jam was caused by warm

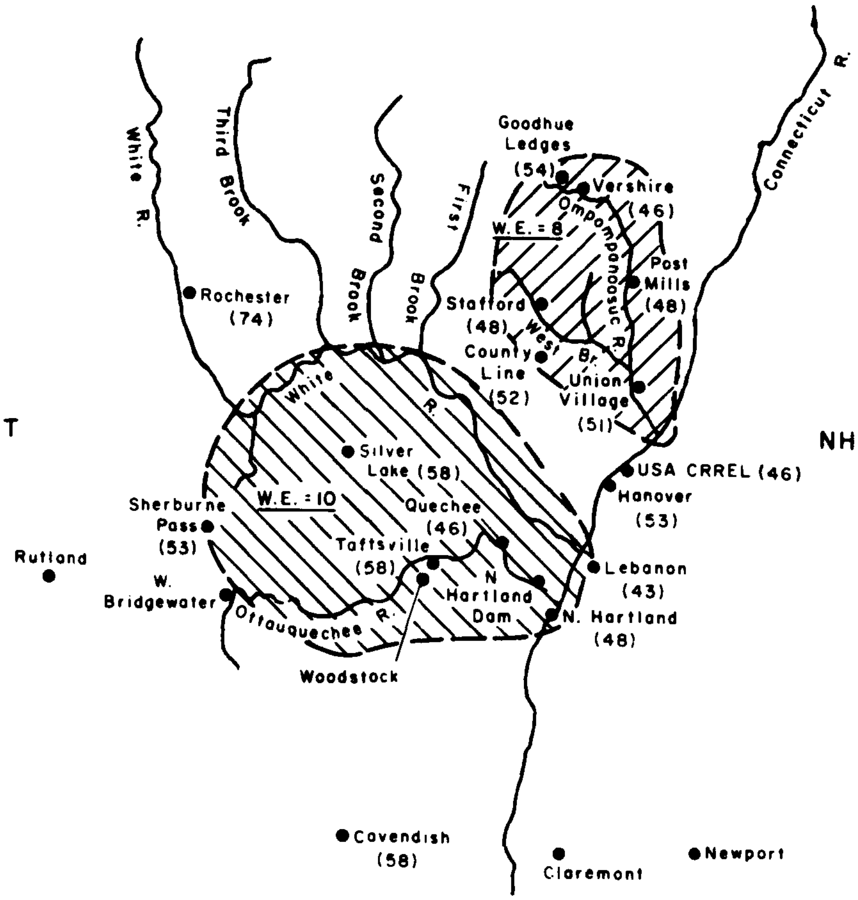


Figure 2. Area with water equivalencies of snow greater than 10 cm, and snow depth prior to rain and during flood of 26-28 January 1976. Numbers refer to snow depth (cm) at particular station.

temperatures and light rainfall on a thin ice cover. Colder than normal air temperatures immediately followed the December jam, facilitating new ice formation. These cold air temperatures rapidly reduced the river flow before the jam could clear itself, allowing the jam to settle to the river bed, and become grounded where it remained the rest of the winter (Bates and Brown 1981). The Ice Engineering Manual (U.S. Army Corps of Engineers 1981) discusses this condition in greater detail. The early jammed and rafted ice increased the probability of severe ice jams and flooding at the end of the winter.

As in January 1976, warm temperatures and an abnormally high rainfall (Table 2 and App. A) combined to cause rapid breakup and severe flooding on 13-14 March 1977. Several days prior to the rain, temperatures reached 5° to 7°C above the monthly mean of 1.9°C, which was itself 3.3°C above the

Table 2. Precipitation comparison for local stations, March 1977 (mm).

Station	Normal precipitation	March 1977	% normal	Amount of precipitation during flood	% March 1977 precipitation
Hanover	66	102	154.5	34	33.3
Woodstock	77	126	163.6	53	42.1
Rochester	84	134	159.5	50	37.3
Cavendish	86	150	174.4	67	44.7
Average	78 mm	128 mm	163.0%	51 mm	39.3%

long-term average temperature for March (U.S. Dept. of Commerce 1964). During March, 126 mm of precipitation was recorded, 163.6% of the normal of 77 mm for the Woodstock area (Table 2). Of this precipitation, 52.8 mm (42% of the month's total precipitation) was measured at Woodstock in the period 13-14 March (see Fig. 3d and 4 and App. A). The snow cover with its high water equivalent (Fig. 3a and 5, U.S. Dept. of Commerce 1973, U.S. Army Corps of Engineers 1976-1978) disappeared virtually overnight at Woodstock and at other sites throughout the local area (U.S. Dept. of Commerce 1976-1978, Woodstock Wastewater Treatment Plant 1975-1978, U.S. Army Atmospheric Sciences Laboratory 1975-1978).

The combination of warm temperatures, heavy precipitation, high water equivalencies and a previously grounded and rafted ice cover resulted in flooding, bank erosion and destruction along the Ottauquechee River basin. Ice flowed over roads near the river. The Quechee Lakes golf course bridge and a log boom across the river at the North Hartland Dam backwater were both taken out by the ice jam.

Comparison to the Winter of 1977-78

Thus far, two severe ice jams have been described. The question remains as to why the winter of 1977-78 did not include any severe ice jamming or flooding.

In contrast to the January 1976 jam/flood, two small jams in January 1978 did not clear all the existing ice cover. Some ice movement occurred during the 24-26 January 1978 ice jam, but significant amounts of grounded and rafted ice did not form in the river. Therefore, in contrast to the previous winter, early small ice jams were not a problem during the 1978 spring breakup.

Differences in river ice cover thicknesses do not completely account for the lack of a severe ice jam in the 1977-78 winter. Meteorological

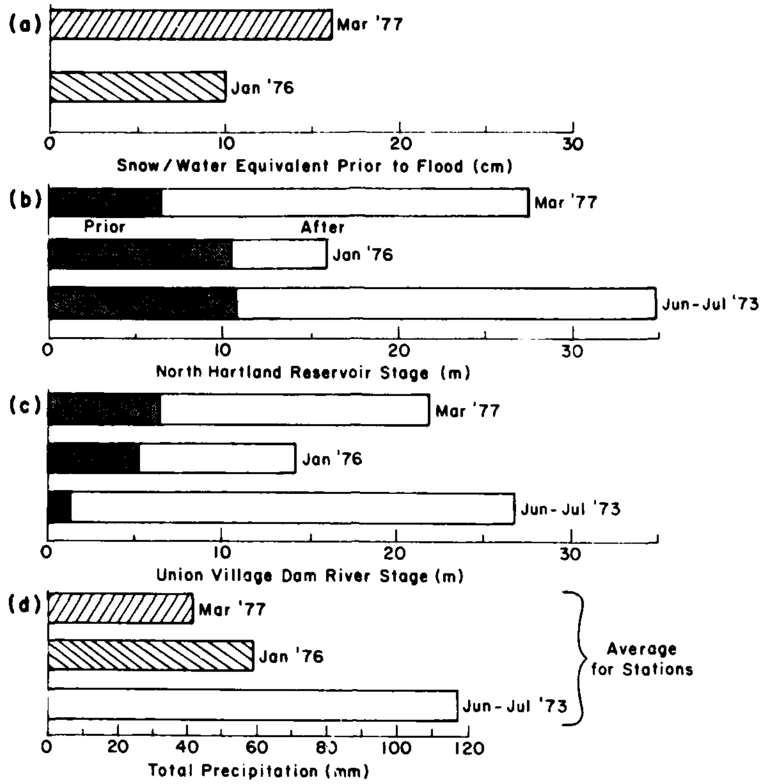


Figure 3. Snow water equivalencies, stage heights and precipitation totals.

conditions similar to those for the 1977 rapid breakup did not occur in the spring of 1978 so that high water levels and flooding were not a problem. The gradual melting of the ice in March 1978 is attributed to the slow diurnal warming trend (i.e. air temperatures slightly above freezing during the day with freezing temperatures at night). This trend permitted a slow continual breakup of the ice. The associated gradual warming of the water upstream in open areas also aided this type of spring breakup (Bates and Brown 1981).

Furthermore, as demonstrated in Table 3 and Figures 3b and 3c, the river stages at Union Village Dam and at North Hartland Reservoir were much higher in the summertime flood than in either wintertime flood. The reason for lower stage levels during the wintertime floods is reflected in the nature of the river ice cover. The rafted ice cover and jamming upstream formed a dam that restricted peak water flow from reaching the North Hartland Flood Control Dam recording gage. The increased water flow down the river caused by rain and tributary flow raised the level of the ice cover

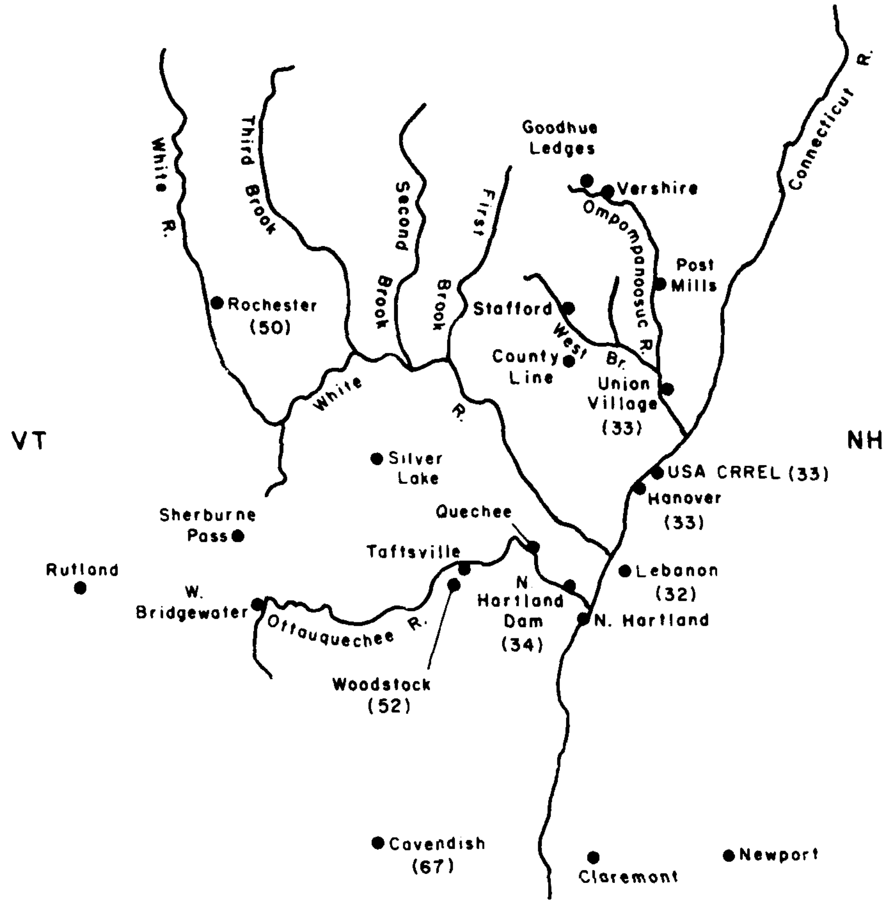


Figure 4. Amount of precipitation (mm) received during flooding of 13-14 March 1977 (numbers = amount of precipitation).

Table 3. A comparison of river and reservoir stages (m) during the three floods.

	Before	Peak value during flood
Union Village Dam River Stage		
28 June - 1 July 1973	1.2	26.8
26 January - 28 January 1976	5.2	14.2
13 March - 14 March 1977	6.4	21.9
North Hartland Reservoir Stage		
28 June - 1 July 1973	10.8	34.7
26 January - 28 January 1976	10.5	15.7
13 March - 14 March 1977	6.4	27.6

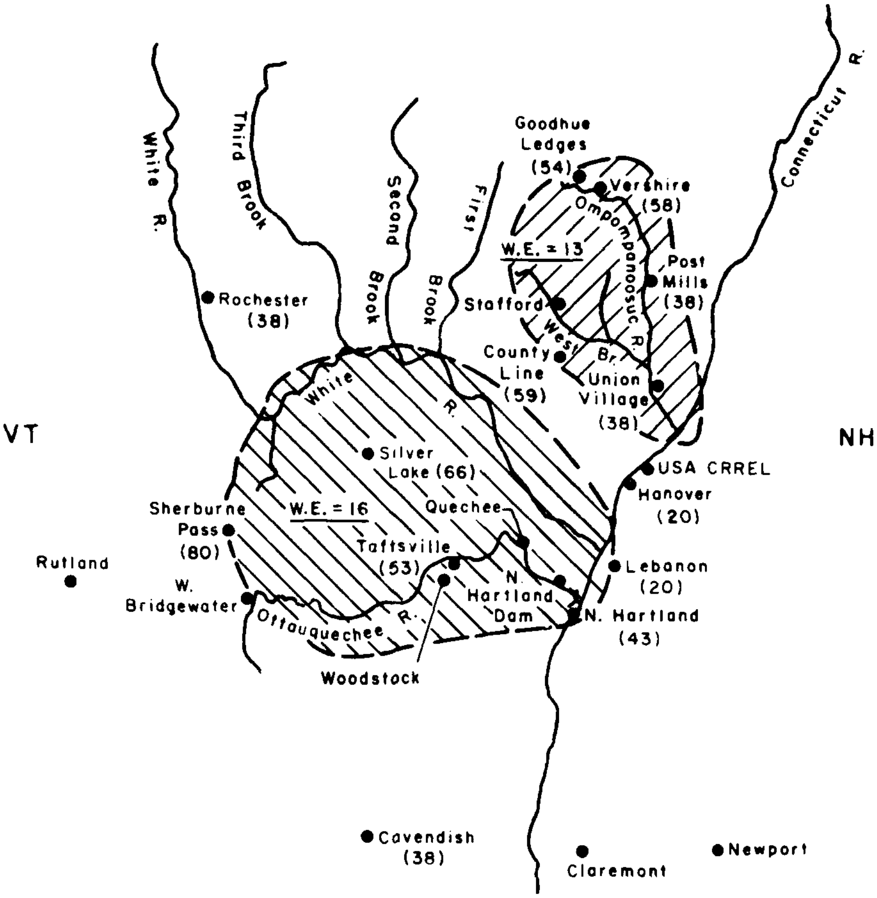


Figure 5. Area with water equivalencies of snow greater than or equal to 16 cm, and snow depths prior to rain and flood of 13-14 March 1977 (numbers = snow depth).

which was weakened in both January 1976 and March 1977 by warm temperatures and runoff from the high water equivalency of the snow cover (Fig. 2, 3a, 5). Given these meteorological conditions, the weakened ice broke up and moved downstream, where it became grounded and jammed at the various locations along the Ottauquechee River.

In March 1977, some grounded and rafted ice from the December 1976 jam still remained in the river. Since the old jam stopped the runoff, additional natural barriers were created. However, regardless of whether an old ice jam or channel morphology causes the original obstruction of the river flow, a jam rapidly increases in size once the ice is stopped at <u>any</u> location. The river channel is constricted by ice, subsequently backing up the upstream water and flooding rapidly occurs. As described in the Ice Engineering Manual (U.S. Army Corps of Engineers 1981), "the situation is

not like a normal open water flood [i.e. June-July 1973] when the channel is not large enough for the flow. Instead the channel is completely blocked. So normal back-water calculations based upon stage level recorders are meaningless. Suddenly there is a new dam in the river...which is creating a lake and which has no convenient spillway."

This description explains why the river and reservoir outflow stage levels were not as high in the two wintertime floods as in the summertime flood. The ice cover and jammed ice upstream prevented peak water flow from reaching the recording gage at the North Hartland Dam. It is also apparent why less precipitation is needed in the winter (and especially when previous small grounded jams exist in the river, as demonstrated in March 1977) than in the summer in order to initiate flooding situations.

CLIMATE CONDUCIVE TO ICE JAM FORMATION

While sudden warm wintertime air temperatures can cause rafting and jamming of ice, a sharp rise in air temperatures accompanied by heavy rainfall (which increases the influx of water from tributaries) on a high water equivalent snow cover increases the likelihood of severe ice jams (January 1976, March 1977). From analysis of the Ottauquechee River data, it appears that greater than 3 cm of warm wintertime rain in a 24-hour period on a high water equivalent snow cover is sufficient to cause jamming of the ice and subsequent flooding on this river.

Some grounding, rafting, and jamming of the ice cover typically occurs in the spring, as the ice does not have sufficient time to melt in place. However, meteorological conditions directly influence the severity of this occurrence. For example, the spring of 1978 experienced a gradual rise in temperatures, followed by normal rainfalls. Thus, flooding and jamming did not cause serious problems. In contrast, in the spring of 1977 heavy rain and a sharp increase in the air temperature occurred simultaneously, resulting in a severe ice jam.

Given the appropriate meteorological conditions, ice jamming is possible at any time during the winter. Whereas the weather determines <u>when</u> an ice jam will occur, channel morphology is the significant determinant of <u>where</u> an ice jam will occur (Calkins et al. 1978, Gatto 1978, Ashton 1979). As defined by Calkins et al. (1978), "Areas...where ice jams generally form are: 1) constrictions; 2) exposed outcrops and man-made structures (bridge piers); 3) long, low velocity, deep water pools; and 4)

shallow sections across portions of the channel where grounding of ice floes could be initiated." Areas along the Ottauquechee River which are susceptible to grounding and jamming of ice are outlined as follows:

1. Bridges: Elm St. Bridge in Woodstock
   Quechee Lakes Bridge (see Fig. B1)
2. Dams/ponds: Taftsville Pond
   Quechee Mill Pond
   Hartland COE Dam/Pond
3. Near the Woodstock sewage treatment plant (double oxbow)
4. Deep-water pools and low water velocity areas where there is little elevation change (thus facilitating grounding of the ice cover).
5. Shallow areas where the river bends or changes direction.

COMPARISONS BETWEEN WINTER AND SUMMER TYPES OF FLOODING

General Comments

The extent of flooding in areas of the Ottauquechee River basin as a result of the January 1976 and March 1977 ice jams was somewhat smaller than recorded for the July 1973 flood which rated as a 50-year recurrence flood (see Fig. B10). The Ottauquechee River basin received an average of 118 mm of rain (Fig. 3d) in the period from 28 June to 1 July 1973 (see Fig. 6). This rainfall was double the average of 60 mm received from 26 to 28 January 1976 and nearly three times the average of 42 mm received during the period 13 to 15 March 1977 (Fig. 3d and Table A3). Considerable bank erosion is evident during summer flooding as compared to wintertime flooding when the ground is frozen. Appendix B shows photos of both conditions. Extensive flooding still occurred in the two wintertime floods, even though less than half of the total summertime 1973 flood precipitation was reported. This shows considerable water contribution from snowmelt.

Synoptic Conditions

Daily weather maps, weekly series, are received at CRREL on a continuous basis from the National Weather Service of NOAA. The synoptic analyses for 0700 e.s.t. from these daily maps are shown for the two wintertime floods: 25-28 January 1976 (Fig. 7) and 13-16 March 1977 (Fig. 8). Also, synoptic conditions for 28 June to 1 July 1973 are shown in Figure 9 for the summertime flood that resulted from heavy rainfall. These

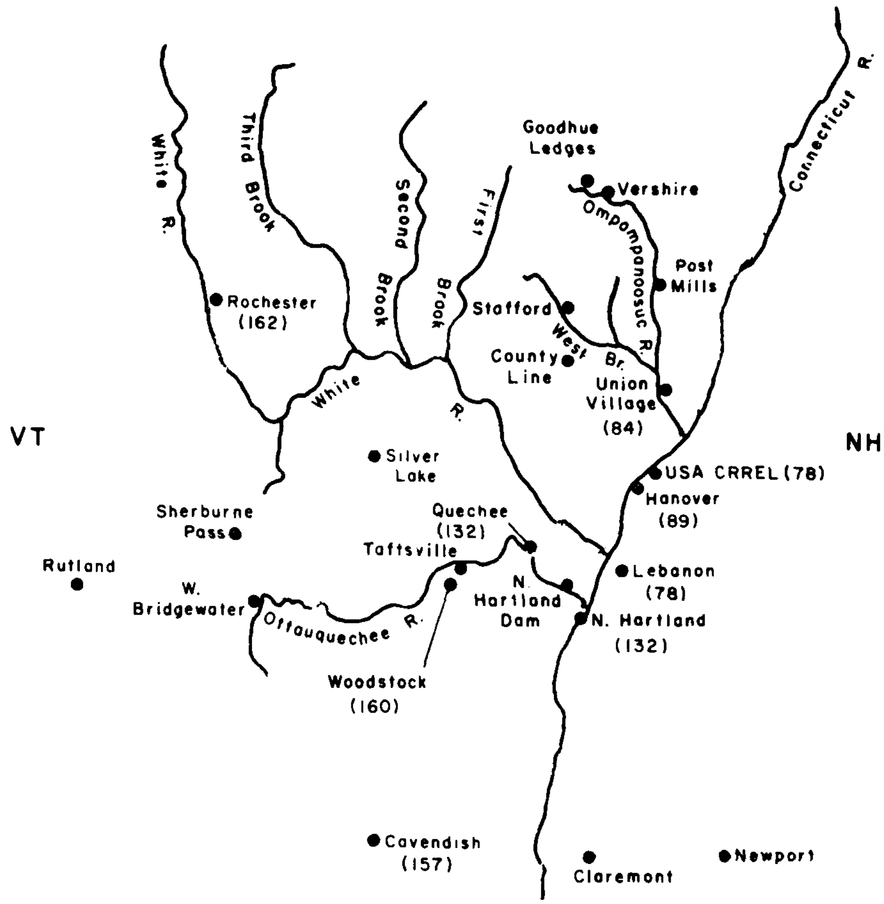
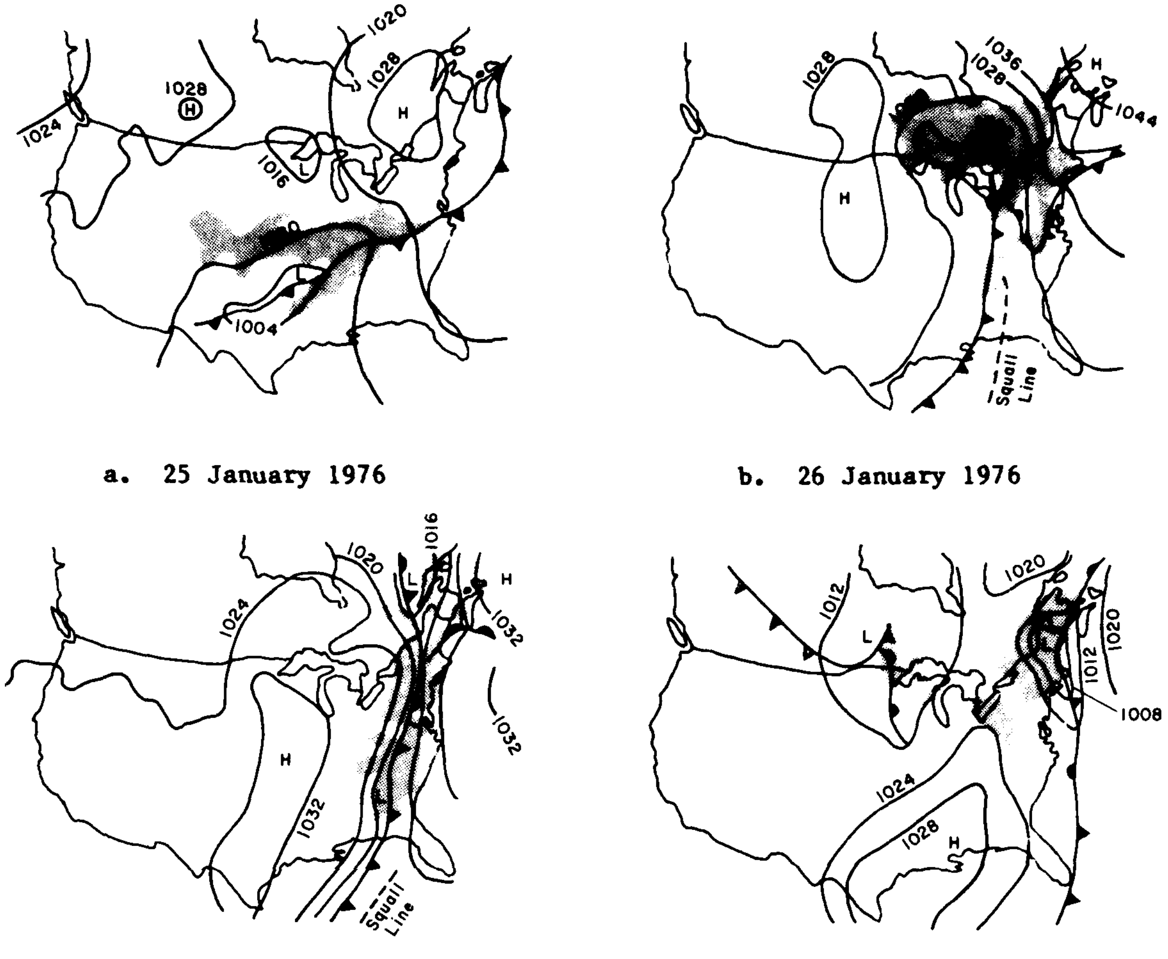


Figure 6. Amount of precipitation (mm) received during flood of 28 June - 1 July 1973.

synoptic maps show that the precipitation (which was a major cause of the wintertime ice jams and flooding) in each case was the result of a well-developed, occluded frontal system extending from a low pressure center having an associated warm sector or rain area.

In contrast, the summer flood of 1973 was induced by a fairly stationary frontal system with associated severe thundershowers. These storms produced heavy rainfall on soil previously saturated from an already above-normal rainfall month. This summertime frontal system was blocked by a high pressure cell off the east coast of New England (see Fig. 9) which remained stationary in the mountains of central Vermont. Heavy rainfall continued for more than three days and greater than 160 mm of rainfall occurred at the center of the storm during this 3- to 4-day time period (Table A3).



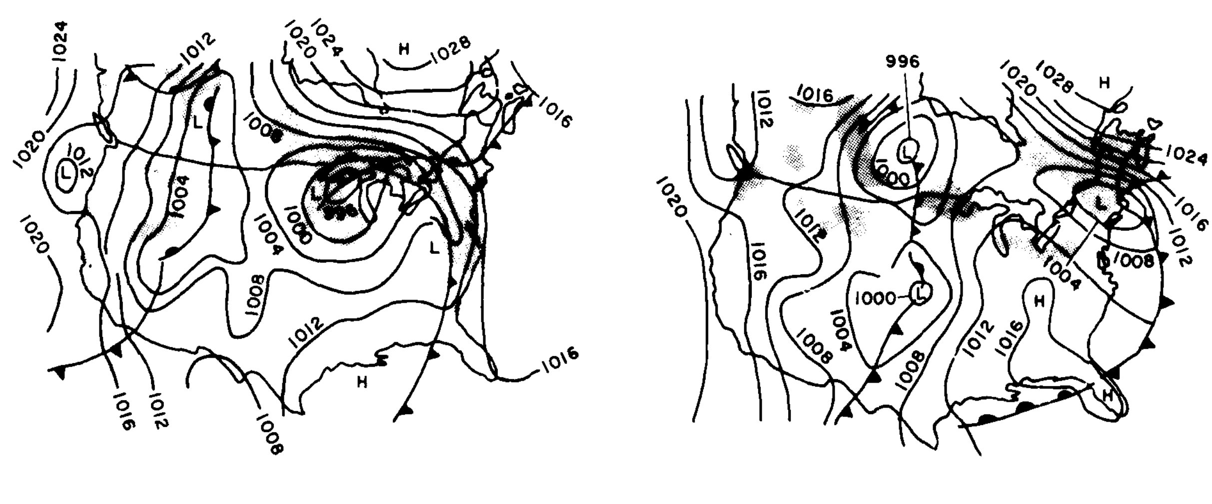
a. 25 January 1976

b. 26 January 1976

c. 27 January 1976

d. 28 January 1976

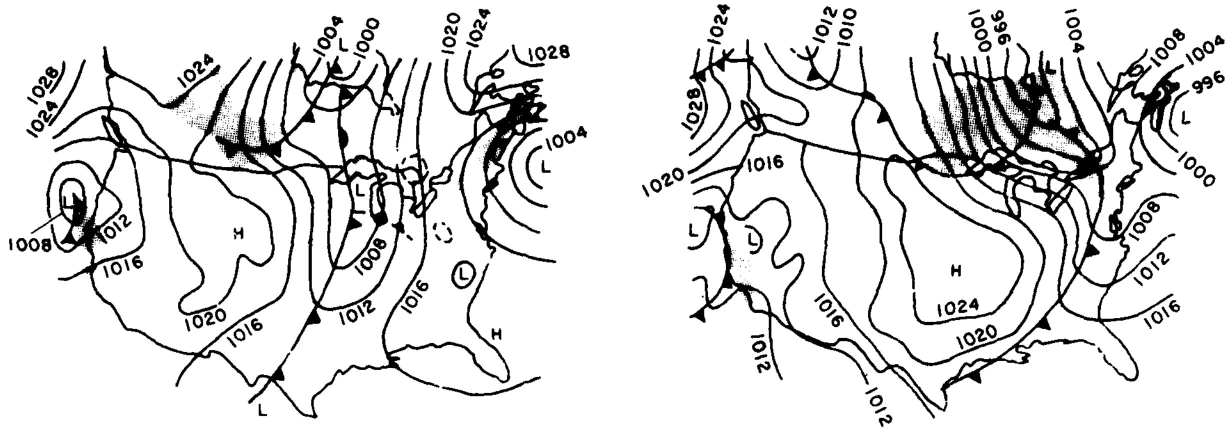
Figure 7. Synoptic weather analyses at 0700 e.s.t. for 25-28 January 1976.



a. 13 March 1977

b. 14 March 1977

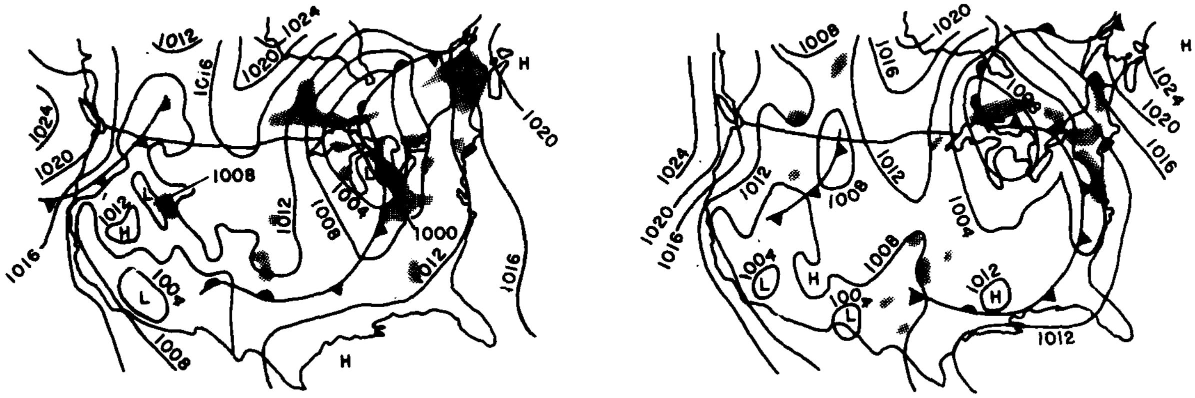
Figure 8. Synoptic weather analyses at 0700 e.s.t. for 13-16 March 1977.



c. 15 March 1977

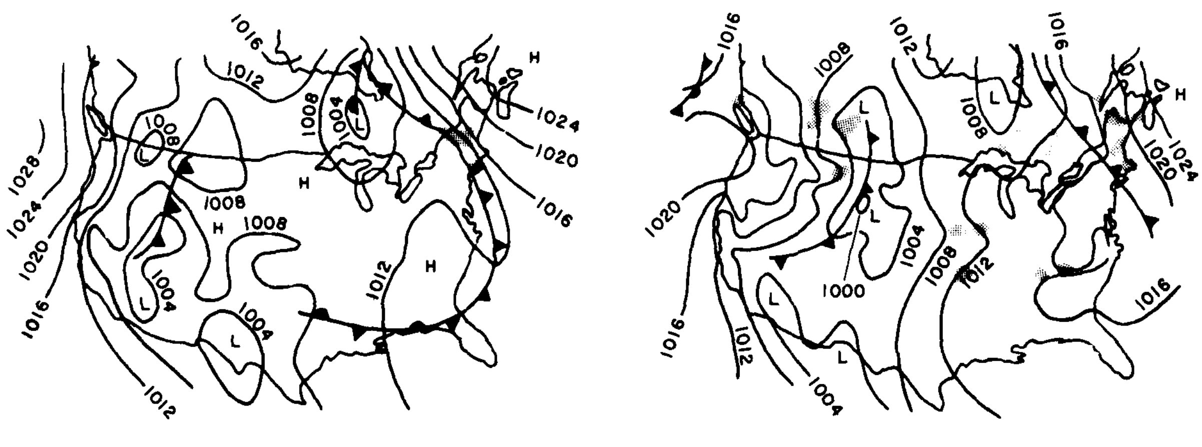
d. 16 March 1977

Figure 8 (cont'd). Synoptic weather analyses at 0700 e.s.t. for 13-16 March 1977.



a. 28 June 1973

b. 29 June 1973



c. 30 June 1973

d. 1 July 1973

Figure 9. Synoptic weather analyses at 0700 e.s.t. for 28 June - 1 July 1973.

SUMMARY AND CONCLUSIONS

This report discusses wintertime meteorological conditions that induce rapid ice breakup, ice jam formation and subsequent flooding. During three winters of study (November 1975-April 1978) two major ice jams and concurrent high water levels occurred in the Ottauquechee River basin of Vermont. These ice jams and high water levels took place during 26-28 January 1976 and 13-14 March 1977. Both ice jams occurred after 2 to 4 days of warm wintertime air temperatures (6°-10°C daily average) and heavy rainfall (50 to 60 mm) in a two-day period. Water equivalents of the snow averaged 10 cm prior to the January 1976 flood and 16 cm prior to the March 1977 flood. Most of this high density snow cover (greater than 0.30 g/cm^3) melted during the two time periods analyzed. The melted snow cover and heavy rainfall runoff produced high water level flows on the frozen river. This provided a mechanism for rafting and jamming in areas prone to ice jams.

The severe summertime flood of 28 June to 1 July 1973, caused by heavy precipitation, is also considered in this report. Comparisons are made (total precipitation, stage height and the synoptic situation) between the summertime flood and a wintertime ice jam and high water situation. Analysis shows that winter floods are usually the result of a large jam restricting or completely blocking the channel, together with a high flow of water entrapped behind the ice dam. Therefore, warm temperatures and a heavy wintertime rainfall on a snow cover with a high water equivalent could cause water levels significantly higher than those for a summertime event having considerably more rainfall. However, this water level is not reflected in wintertime gage readings due to the presence of the upstream jams.

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APPENDIX A: CLIMATIC COMPARISON FOR LOCAL STATIONS, 25-28 JANUARY 1978 AND 8-16 MARCH 1977

Table A1. Comparison for 25-28 January 1976.

Date	Hanover	Union Village Dam	CRREL	Lebanon FAA	Woodstock	Rochester	Quechee Dams	Cavendish	Remarks
Precipitation (mm)									
1/25	2	T	0	T*	0	1	0	T	
1/26	8	1	17	15	5	7	2	11	
1/27	29	24	27	31	25	44	23	24	
1/28	21	37	9	9	34	35	30	23	
Max. temperature (°C)									
1/25	-3.3		- 3.3	2.8	-10.0	-13.9	-12.8	- 2.8	
1/26	0.6		1.7	1.1	0.0	- 1.7	- 2.8	0.6	
1/27	7.8		8.3	8.9	6.1	8.3	7.8	3.9	
1/28	2.2		1.7	0.6	4.4	6.1	8.3	1.7	
Min. temperature (°C)									
1/25	-16.7		-18.9	-17.2	-20.6	-25.0	-20.6	-18.9	
1/26	- 8.3		- 3.3	- 6.7	-15.6	-20.6	-18.3	- 6.7	
1/27	- 2.2		1.7	0.0	- 1.1	- 2.8	- 2.2	- 0.0	
1/28	- 5.0		- 6.7	- 7.2	- 0.0	- 2.2	0.6	- 3.9	
Mean temperature (°C)									
1/25	-10.0		-11.1	-10.0	-15.3	-19.4	-16.7	-10.8	
1/26	- 3.9		- 0.8	- 2.8	- 7.8	-11.1	-10.0	- 3.1	
1/27	2.8		5.0	4.4	2.5	2.8	2.8	1.9	
1/28	- 1.7		- 2.5	- 3.3	2.2	1.9	4.4	- 1.1	
Snow depth (cm)									
1/25	53		46	43		74		58	
1/26	51	50	41	43		71	46	53	
1/27	43		36	43		46		48	
1/28	41		33	30		46		46	

* Trace

Table A2. Comparison for 8-16 March 1977.

Date	Hanover	Union Village Dam	CRREL	Lebanon FAA	Woodstock	Rochester	Cavendish	Remarks
					Precipitation (mm)			
3/13	29	3	27	27	5	3	38	On 3/19 Woodstock had 17 mm precipitation
3/14	2	28	4	3	45	45	27	
3/15		2	2	T	2	2	T	On 3/4 Woodstock had 34 mm precipitation
3/16	2			2			2	
					Max. Temperature (°C)			
3/8	7.8		7.2	7.2	4.4	7.8	6.7	
3/9	15.6		13.9	15.6	6.7	15.6	15.0	
3/10	18.3		17.2	18.9	13.9	15.6	17.8	
3/11	18.3		17.2	19.4	17.2	16.7	15.6	
3/12	17.2		16.7	17.8	15.0	17.2	15.6	
3/13	12.2		10.6	10.0	14.4	17.8	8.9	
3/14	10.0		10.0	8.9	8.3	8.9	5.0	
3/15	10.0		8.9	9.4	6.1	6.1	7.8	
3/16	7.8		5.6	6.7	9.4	10.0	6.1	
					Min. Temperature (°C)			
3/8	- 2.2		- 39.	- 1.1	- 4.4	- 4.4	- 4.4	
3/9	- 5.0		- 6.7	- 5.6	- 6.7	- 6.7	- 7.2	
3/10	2.2		- 1.7	1.1	- 3.9	- 6.7	- 3.3	
3/11	- 2.2		- 3.9	- 2.8	- 2.8	- 3.9	- 5.0	
3/12	- 2.2		- 3.9	- 2.2	- 4.4	- 3.9	- 4.4	
3/13	3.3		2.2	3.3	- 5.0	- 3.9	1.1	
3/14	5.0		3.3	3.3	1.7	1.7	1.1	
3/15	2.2		1.7	2.2	1.1	1.7	1.1	
3/16	2.8		0.6	1.7	1.1	1.1	1.1	

Table A2. (cont.)

Mean Temperature (°C)

3/8	2.8	1.7	3.1	0.0	1.7	1.1	1. Leb. 20 cm snow, melted 3/12-17
3/9	5.3	3.6	5.0	0.0	4.4	3.9	2. UVD 38 cm snow on 1/13; trace 3/14; 13 cm snow 3/18
3/10	10.3	7.8	10.0	5.0	4.4	7.2	3. <u>Snow melted almost overnight</u>
3/11	8.1	6.7	8.3	7.2	6.4	5.3	
3/12	7.5	6.4	7.8	5.3	6.7	5.6	a. Hanover 13 cm 3/9, 0 cm 3/10
3/13	7.8	6.4	6.7	4.7	6.9	5.0	
3/14	7.6	6.7	6.1	5.0	5.3	3.1	b. CRREL 10 cm 3/12 Trace 3/13
3/15	6.1	5.3	5.8	3.6	4.2	4.4	
3/16	5.3	3.1	4.2	5.3	5.6	3.6	

Table A3. Precipitation comparison (mm) for the three floods.

	1973	1976	1977
Hanover	89	60	33
CRREL	78	53	33
Lebanon	78	55	32
N. Hartland Dam	132	56	34
Cavendish	157	35	67
Woodstock	160	64	52
Rochester	162	87	50
UVD	84	62	33
Average	117.5	59.0	41.6

APPENDIX B: FLOOD PHOTOGRAPHS

Figure B1. January 1976, Quechee.

Figure B2. January 1976, Quechee.

Figure B3. January 1976, Quechee.

Figure B4. December 1976, Taftsville.

Figure B5. December 1976, Taftsville.

Figure B6. December 1976, Taftsville.

Figure B7. March 1977, Quechee.

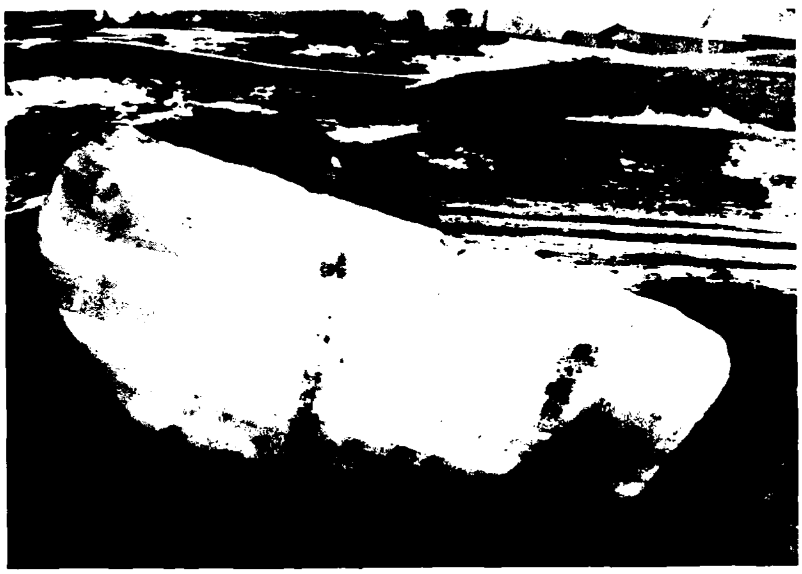

Figure B8. March 1977, Quechee.

Figure B9. March 1977, Quechee.

a. High water, July 1973.

b. High water, July 1973.

c. Bank erosion, July 1973.

d. Bank erosion, July 1973.

Figure B10. Examples of high water levels and bank erosion.